Macroscopic manifestation of the strong nuclear interaction in the optical spectra of solids

V. G. Plekhanov

Fonoriton Sci. Lab., Garon Ltd., Lasnamae 22 - 3, Tallinn 11413, Estonia

Abstract. Artifical activation of the strong interaction by adding of one neutron to the nucleus causes the global reconstruction of the macroscopic characteristics of solids.The experimental evidence of macroscopic manifestation of the strong interaction in optical spectra of solids which are differ by term of one neutron from each other has been presented. This evidence is based on two independent results: 1) The increase exciton energy on 103 meV is caused by the adding of one neutron (using LiD crystals instead LiH ones); 2) After increasing the amounts by one neutron the energy of LO phonons has decreased by 36 meV. The last one is directly seen from luminescence and scattering spectra. As far as the gravitation, electromagnetic and weak interactions are the same in both of kind crystals, it only changes the strong interaction. Therefore a logical conclusion is made that the renormalization of the energy of electromagnetic excitations (excitons, phonons) is carried out by the strong (nuclear) interaction. The Standard Model is insufficiently underlined.

I. Introduction

As is well known, the neutron is not only an investigation object but also a powerul instrument of the study of the nucleus and condensed matter properties. The neutron is one of the main particles of the Standard Model (SM) [1] which is perfectly described by Quantum Chromodynamics (QCD)[2]. Our present knowledge of physical phenomena suggests that there four types of forces between physical bodies (see, e.g. [3, 4]):
1) gravitational;
2) electromagnetic;
3) strong;
4) weak.
Both the gravitational and the electromagnetic forces vary in strength as the inverse square of the distance and so able to influence the state of an object even at very large distances whereas the strong and the weak forces fall off exponentially and so act only at extremely short distances. The strong forces does not act on leptons (electrons, positrons, muons and neutrinos), but only on protons and neutrons (more generally, on baryons and mesons - this is the reason for the collective name hadrons). It holds protons and neutrons together to form nuclei, and is insignificant at distances greater than 10^{-15} m [3]. Its macroscopic manifestations are restricted up to now to radioactivity and the release of nuclear energy. The three forces which are relevant to elementary particles can be recognized in the three kinds of radioactivity: α - radiation is caused by the strong force, β - radiation by the weak force, and γ - radiation by the electromagnetic force. The characteristics of these forces are summarized in Table 1.

Table 1. **The four fundamental forces**

Interaction	FQ	Mass	Range (m)	RS	Spin	TC - S (m^2)	TTS (s)
Strong	Gluon	0	10^{-15}	1	1	10^{-30}	10^{-23}
Weak	$W^{\pm}$, Z	81, 93 GeV/c^2	10^{-18}	10^{-5}	1, 1	10^{-44}	10^{-8}
Electromagnetic	Photon	0	∞	$\alpha = 1/137$	1	10^{-33}	10^{-20}
Gravity	Graviton	0	∞	10^{-38}	2	-	-

Here - FQ field quant, RS relative strength, TC - S Typical cross - section, TTS - Typical time scale.

This table given for the strength and range of the forces come from a comparison of the effects they produce on two protons. In some respect these resemble an ordinary Newtonian force between the protons, varying with the distance between them as if the force was derived from a potential function:

$$V(r) = \frac{ke^{-r/R}}{r^n} \qquad (1)$$

for some n. This is an inverse - power force which is diminished by an exponential factor at distances larger than a certain distance R, the range of the force. The strength of the force is measured by the constant k. The unit of strength is $hc/2\pi$ where h is Planck's constant and c the speed of light. We should add that the weak force does not appear to be particularly weak on this reckoning: the reason for its very short range (see Table 1) rather than its intrinsic strength. Since the protons and neutrons which make up the nucleus are themselves considered to be made up of quarks are considered to be held together by the color force [2], the strong force between nucleons may be considered to be a residual color force (see, also [1, 3]). In the SM, therefore the base exchange is the gluon which mediates the forces between quarks. The modern quantummechanical view of the three fundamental forces (all except gravity) is that particles of matter (fermions = neutrons, protons, electrons) do not directly interact with each other, but rather carry a charge, and exchange virtual particles (gauge bosons = photons, gluons, gravitons) which are the interaction carriers or force mediators. As can be see from Table 1, photons are the mediators of the interaction of electric charges (protons, electrons, positrons); and gluons are the mediators of the interaction of color charges (quarks). In our days, the accepted view is that all matter is made of quarks and leptons (see Table 2).

Table 2. Quarks and leptons

	Family 1	Family 2	Family 3	Electric charge (e)
· Leptons	e^-	μ^-	τ^-	- 1
	ν_e	ν_μ	ν_t	0
Quarks	u	c	t	2/3
	d	s	b	- 1/3

As can be see, of the three pairs of quarks and leptons, one pair of each - the quark u and d and the leptons e^- and ν_e^- (electrons neutrino) - are necessary to make up the every day world, and a world which contained only these would seem to be quite possible.

The facts, summarized in the modern nuclear physics (see, e.g. [5, 6]) allow to draw several conclusions in regard to nuclear forces, most notably that the binding energy of a nucleus is proportional to the number of nucleons and that the density of nuclear matter is approximately constant. This lead to conclude that nuclear forces have a "saturation property". It seems from the last conclusion it is enough to change the number of neutrons in nucleus to change strength of nuclear force. But the last one constitutes the main ideas of the isotope effect [4].

Below we will briefly describe the results of the optical spectroscopy of isotope - mixed solids. The apparatus used in our experiments has been described in several previous publications [7 - 9]. For clarity, we should mentioned here that immersion home - made helium cryostat and two identical double - prism monochromators were used . One monochromator was used for the excitation and the other, which was placed at right - angle to the first for analyzing the luminescence and scattering of light. In our experiments we investigated two kinds of crystals (LiH and LiD) which are differ by a term of one neutron.

II. Results

As demonstrated early (see, e.g. review [10]) most low - energy electron excitation in LiH crystals are the large - radius excitons [11]. Exciton luminescence is observed when LiH (LiD) crystals are excited in the midst of the fundamental absorption. The spectrum of exciton photoluminescence of LiH crystals cleaved in liquid (superfluid) helium consists of a narrow (in the best crystals, its half - width is $\Delta E \leq 10$ meV) phononless emission line and its broader phonon repetitions, which arise due to radiative annihilation of excitons with the production of one to five longitudinal optical (LO) phonons (see Fig. 1).

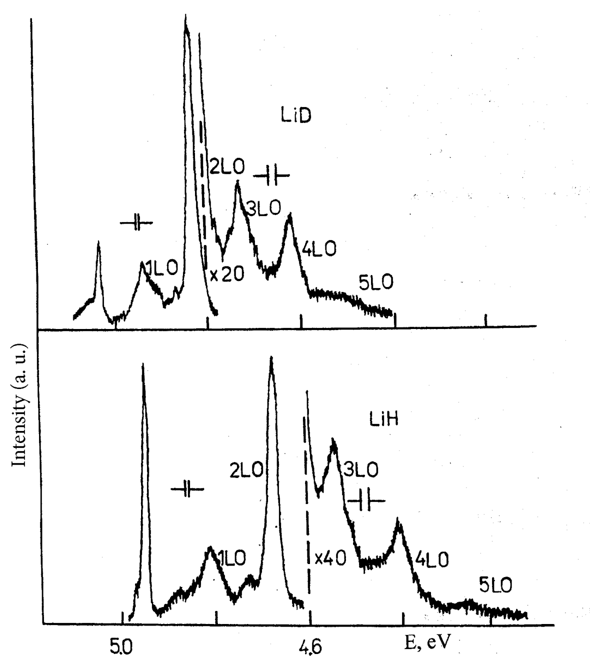

Fig. 1. Photoluminescence spectra of free excitons at 2 K in LiH and LiD crystals cleaved in superluid helium.

The phononless emission line coincides in an almost resonant way with the reflection line of the exciton ground state which is indication of the direct electron transition X_1 - X_4 of the first Brillouin zone [12].The lines of phonon replicas form an equidistant series biased toward lower energies from the resonance emission line of excitons. The energy difference between these lines in LiH crystals is about 140 meV, which is very close to the calculated energy of the LO phonon in the middle of the Brillouin zone [13] and which was measured in [14]. The isotopic shift of the zero - phonon emission line of LiH crystals equals 103 meV. As we can see from Fig. 1 the photoluminescence spectrum of LiD crystals is largely similar to the spectrum of intrinsic luminescence of LiH crystals. There are, however, some distinctions one is related.

Firstly the zero - phonon emission line of free excitons in LiD crystals shifts to the short - wavelength side on 103 meV. The second difference concludes in less value of the LO phonon energy, which is equal to 104 meV.

At the excitation below the intrinsic absorption adge ($E_{n=1s}$ = 5.043 eV for LiD [10]) we have succeeded in observing the multiphonon resonance Raman scattering (RRS) with the creation of up four phonons (Fig. 2). Indeed, the energy difference between peaks in the RRS spectrum is equal the energy of the LO phonons in the center of the Brillouin zone [13].

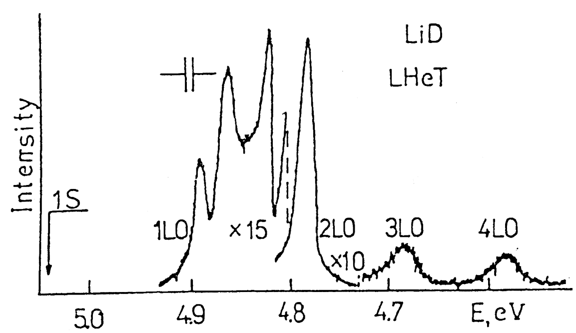

Fig. 2. Resonant Raman scattering of a LiD crystals at the excitation E = 4.992 eV at 4.2 K.

To pay attention the large half - width of observable lines in the RRS spectrum. As was shown in the paper [15] their half - width are always larger than of the excitation line. The proximity of the exciting light frequency to the energy of exciton transitions leads to an essential modification of the selection rules for light scattering. The presence of the second - order TO (Γ) ($\hbar\omega_{TO(\Gamma)}$ = 76 meV for LiH) in the RRS spectrum may be explained by a relatively strong scattering deformation mechanism in these crystals, where, however the main mechanism, as was seen from both figures, is Frőchlich mechanism of intraband scattering. The logwavelength displacement of the excitation line frequency relatively exciton resonance a monotonic decrease the intensity of RRS spectrum as whole more than 60 - fold in both LiH and LiD crystals. Comparison the experimental results on the luminescence and light scattering in the crystals which differ by a term of one neutron only is allowed to the next conclusions;

1. At the adding one neutron (using LiD crystals instead LiH ones) is involved the increase exciton energy on 103 meV.
2. At the addition one neutron the energy of LO phonons is decreased on the 36 meV, that is direct seen from luminescence and scattering spectra. Both characteristics are macroscopic.

III. Discussion

The modern concept of the atom emerged at the beginning of the 20th century , the particular as a result of Rutherford's experiments [5,6]. An atom is composed of a dense nucleus surrounded by an electron cloud. The nucleus itself can be decomposed into smaller particles. After the discovery by Chadvick of the neutron in 1932, there was no longer any doubt that the building blocks of nuclei are protons and neutrons (collectively called nucleons). The elementary particles came to considered the electron, proton and neutron [1, 4]. The primary aim of nuclear physics is to understand the force between nucleons, the structure of nuclei and how nuclei interact with each other and with other subatomic particles.
As say above, an atom consists of an extremely small, positively charged nucleus (see Fig. 3) surrounded by a cloud of negatively charged electrons. As can we see from Fig. 3 the nucleus is less than one ten - thousandth the size of atom, the nucleus contains more than 99.9% of the mass of the atom.

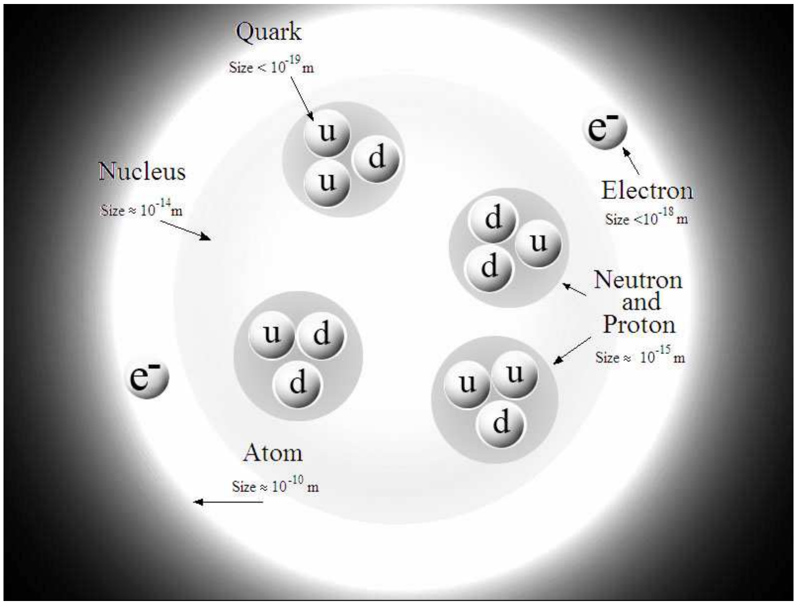

Fig. 3. Structure within the atom. If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across (after http://www.lbl.gov/abc/wallchart/).

Nucleus is central part of an atom consisting of A - nucleons, Z - protons and N - neutrons. The atomic mass of the nucleus is equal Z + N. A given element can have many different isotopes, which differ from one other by the number of neutrons contained in the nuclei [4 - 6]. Modern physics distinguishes three fundamental properties of atomic nuclei: mass, spin (and related magnetic moment) and volume (surrounding field strength) which are source of isotopic effect (see, also [16]).
LiH (LiD) crystals with a lattice of NaCl type, whose parameters are close to cubic crystals, are dielectrics with band gap of E_g = 4.992 eV (E_g = 5.090 eV for LiD) at 2 K [7]. These crystals have

an identical electronic structure. The energy band structure of these substances is also identical. All three kinds of forces - gravitational, electromagnetic and weak are also the same for compounds above. The difference between these substances consists out at one neutron in the nucleus of deuteron. Below we should briefly consider some peculiarities of the physics of deuteron. Nucleons can combine to make four different few - nucleon systems, the deuteron (p + n), the triton (p + 2n), the helion (2p + n) and the α - particle (2p + 2n). These particles are grouped together because they are all stable (apart from triton which has a half - life of about twelve years and so may be treated as a stable entity for most practical purposes), have no bound excited states (except the α - particle which has two excited states at about 20 and 22 MeV [5]), and are frequently used as projectively in nuclear reactions. Few - nucleon systems provide the simplest systems to study nuclear structure (see, e.g. [17]). The deuteron provides important information about the nucleon - nucleon interaction. As was noted, the deuteron consists of a proton and a neutron and is the only bound state of two nucleons. Its binding energy is 2.2245 MeV and its total angular momentum J and parity are 1^+ [6]. Since the intrinsic parities of the neutron and the proton are positive parity of the deuteron implies that the relative orbital angular momentum of the neutron and the proton must be even. If the orbital angular momentum L is a good quantum number, states with lower orbital angular momentum generally have lower energy than states with higher angular momentum, and so we expect the ground state of the deuteron to have orbital angular momentum L = 0, so that it is in an S state. Then, if the spins of the proton and the neutron in the deuteron are parallel, we expect the magnetic moment of the deuteron to be approximately the sum of the magnetic moments of the proton and neutron, namely $\mu_p + \mu_n = (2.793 - 1.913)\mu_N = 0.880\mu_N$ ($\mu_N = \frac{e\hbar}{2m_p}$) [5]. If, however, the spins are anti - parallel , we expect it to be $(2.793 + 1.913)\mu_N = 4.706\mu_N$. Experimentally it is $0.857\mu_N$ [5, 17] so the spins of the proton and neutron are parallel and so the total spin S of the deuteron is one, since J = L + S, J = 1. The small but definite difference between $\mu_d = 0.857\mu_N$ and $\mu_p + \mu_n = 0.880\mu_N$ is due, as will shown below, to tensor character of strong forces in deuteron. We thus conclude that the ground state of deuteron is a triplet S state. However this cannot the whole story because S states are spherically symmetrical and thus have no quadrupole moment. This is contradict to experiments. Experimentally the deuteron has a positive quadrupole moment of 0.29 fm^2 [18]. The deviation of the actual deuterium moment from the S state moment can be explained if it assumed that the deuteron ground state is a superposition of S and D states. Part of the time, the deuteron has orbital angular momentum L = 2. Independent evidence for this fact comes from the observation that, as was shown above, the deuteron has a small, but finite, quadrupole moment (see, also [18]). As is well - known, the electric quadrupole moment measures the deviation of a charge distribution from sphericity [4].

The quadrupole moment of a disk shaped (oblate) nucleus Q is negative. A positive quadrupole moment of Q = 0.29 fm^2 according experiment indicates that the deuteron is slightly elongated the z - axiz, like an olive (prolate). Quantum mechanical definition of quadrupole moment for a single proton [18] is described by:

$$eQ = e\int \Psi^* (3z^2 - r^2)\Psi dt . \qquad (2)$$

Thus, if the quadrupole moment is not equal to zero then the eigenfunction of the ground state of the deuteron assigns a probability of 0.04 to finding a $^3D_1$ state and a probability of a 0.96 to finding a $^3S_1$ state. The last one points to the tensor character of the nucleon - nucleon interaction (the more details see, e.g. [5, 6]). Nuclear magnetic dipole and electric quadrupole have a similar importance in helping us to interpret the deuteron structure.

The motion of the electrons produces a magnetic field $\overrightarrow{B_e}$ at the nucleus, which interacts with the nuclear magnetic moment μ_I (see, e.g. [19]):

$$E = - \overrightarrow{\mu_I} \cdot \overrightarrow{B_e}. \qquad (3)$$

Typical energy differences of hyperfine multiplets are only about 10^{-7} eV (in case of the deuteron it is 3.16 • 10^{-7} eV (see also [20, 21])). This value is by more than seven order less than we observe in experiments: the isotopic shift of the n = 1s excitons is equal to 0.103 eV.

The short range character of the strong interaction doesn't possess direct mechanism of the elementary excitation energy renormalization, which was observed in the experiments. However, there is one not very convincing possible hypothesis of the strong interaction mechanism - this is residual long range electromagnetic interaction of the electric charge quarks. The non - zero value of electric quadrupole moment indicates in favour of this hypothesis, for example, in deuterium. Such hypothesis doesn't contradict to the conclusion of the papers [1, 2, 3, 20, 21, 22] about the mass difference origin between the neutron and proton connected with electric charged u and d quarks. Moreover, the neutron mass diminishing in nuclei in comparison to the free state of neutron independently shows the actual residual electromagnetic interaction in nucleons between quarks (see, also [20] and references therein). Naturally, the origin of Van der Waals*) or new type forces are in need of more quantitative not only experimental but also theoretical investigations of observed effects.

Nevertheless, we have very close of the isotope shift exciton energy in the case $^{12}C_x^{13}C_{1-x}$ diamond crystals to the indicated value above in LiH crystals. Indeed, in such experiments we have isotope shift in $^{12}C_x^{13}C_{1-x}$ diamond crystals approximately 15 meV [4] per one neutron and on seven neutrons we get 15 • 7 = 105 meV. This value is very close to the observed one (103 meV) in LiH crystals.

Thus, the tentative interpretation of describing experimental results don't find consistent explanation at the change strong interaction leaving it to be another mystery of SM (see, also [20, 21]). We should remind that intrinsic contradiction of SM is already well - known. Really, the Lagrangian of QCD (theory of the strong interaction) describes both free motion and interaction between quarks and gluons, which is defined by the strength couple g, its eigenstates are the quarks and the gluons which are not observed in free states [2, 21, 22]. The observed hadrons in the experiment don't eigenstates in quantum chromodynamics. It is obvious to expect that the modern theory of QCD should finally overcome these difficulties [20]. We should add that the current theoretical and experimental evidence for the existence of electronic objects with a fractional of electron charge (e/2, e/3, etc) is reviewed in paper [23]. One more possible mechanism the influence of the strong interaction on the dynamics of elementary excitation connects with the zero - point vibration [4, 20, 21].

Conclusion

The experimental evidence of the macroscopic manifestation of strong (nuclear) interaction in optical spectra of solids which are differ by term of one neutron from each other has been presented for the first time. This evidence is based on two independent experimental results, which is directly seen from luminescence and scattering spectra. As far as the gravitation, electromagnetic and weak interactions are the same in both of kind crystals, it only changes the strong interaction. Therefore a logical conclusion is made that the renormalization of the energy of electromagnetic excitations (excitons, phonons) is carried out by the strong (nuclear) interaction. There is underlined the necessity consideration the strong (nuclear) interaction in quantum electrodynamics.

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*) Estimation of the Van der Waals force, for example, dispersion character gives more than 25 times hydrogen polarization value decrease and this is not correct.

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